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Model simulation of Greenland Sea upper-ocean variability

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[1] Observations indicate that the occurrence of dense upper-ocean water masses coincides with periods of intense deep-water formation in the Greenland Sea. This paper focuses on the upper-ocean hydrography of the area and its simulation in models. We analyze properties that reside below the summer mixed layer at 200 m and carry the winter mixing signal. The analysis employs numerical simulations from four different models, all of which are forced as specified by the Arctic Ocean Model Intercomparison Project (AOMIP). The models exhibit varying degrees of success in simulating upper-ocean properties observed in the Greenland Sea, including very dense, saline water masses in the 1950s, 1960s, and 1970s. Two of the models predict the importance of salinity in determining the maximum density in the upper waters of the central gyre. The circulation pattern of Atlantic Water was captured well by two high-resolution models as measured by temperature-salinity-density relationships. The simulated temporal variability of Atlantic Water properties was less satisfactory, particularly in the case of salinity.

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1. Introduction

[2] Modeling the Nordic Seas, and the Greenland Sea in particular, is a challenging task because the area is characterized by a complex system of exchanges among adjacent oceans and strong topographic influence on ensuing processes. The last 50 years have seen large fluctuations in the stratification structure of the Greenland Sea. Years prior to 1980 were dominated by a weakly stratified, domed structure whose center was filled with newly formed Greenland Sea Deep Water (GSDW). Since 1980, the domed structure has gradually flattened and is associated with warming of GSDW due to lack of deep convection [*Schlosser et al.*, 1991; *Bonisch et al.*, 1997; *Budeus et al.*, 1998; *Osterhus and Gammelsrod*, 1991; *Karstensen et al.*, 2005]. The new approach of using chlorofluoromethanes F11 and F12 to measure ventilation of deep waters showed that the renewal rates had significantly decreased by 1993 and especially from the reference period of 1982–1989 [*Rhein*, 1991, 1996]. As the central gyre has grown fresher and more stratified since the mid 1980s, warming of the core of the incoming Atlantic Water has accelerated [*Blindheim and Osterhus*, 2005, Figure 6]. These trends would require extremely large buoyancy losses in order to return the Greenland Sea upper (and lower) ocean stratification to the conditions prior to 1980.

[3] The focus of this study is to investigate how well we can simulate upper-ocean conditions of the Greenland Sea because we presume that preconditioning of the upper ocean is important for dense water production. With increasing density in the upper ocean there is a corresponding increase in the likelihood that deep-water formation can occur. Arctic Ocean simulation depends upon adequate simulation of upper-ocean conditions in the Nordic Seas. Exchanges between the North Atlantic and Arctic Oceans are thought to influence Nordic Seas processes as much as local forcing. Modified Atlantic Water continues to the Arctic, where it undergoes further modification before emerging again beneath the surface in the Nordic Seas. Thus, capturing upper-ocean variability in the Greenland Sea in particular is a preamble for successful Arctic Ocean simulation.

[4] Our model simulations incorporate results from models limited to the Arctic and Nordic Seas as well as models with an active connection to the North Atlantic Ocean. In principle, temperature simulation should be successful because the upper-ocean heat content is in equilibrium with the local atmospheric flux on seasonal time scales. A complication is presented by advection of heat from the main North Atlantic Ocean, which provides a major contribution to the heat balance in the Nordic Seas. Advection is even more critical for the salt balance, which, combined with not-so-well determined fluxes of fresh water and runoff, makes successful simulation of salinity difficult. One measure of model success at simulating interaction with the North Atlantic is the timing and amplitude of the Great Salinity Anomaly [*Dickson et al.*, 1988], which started its passage through the Nordic Seas around 1976–1978. It will become apparent that the models discussed are

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far from perfect, but progress toward higher resolution may eventually improve their simulations.

[5] Sections 2 and 3 of this paper provide general descriptions of models and surface forcing, respectively. Section 4.1 probes mutual relationships between salinity, temperature, and density fluctuations, and section 4.2 discusses time evolution through the center of the Greenland Sea convection area (75°N). Section 4.3 explores whether the simulated upper-ocean density maximum along 75°N is related to salinity, as observations suggest, or to temperature. The simulated Atlantic Water properties are discussed in section 4.4.

5. Summary

[21] This study surveys simulated hydrographic properties for the Greenland-Iceland-Norwegian Seas from a range of models using either z- or sigma-levels in the vertical, a C or B grid in the horizontal, and a range of resolutions in the horizontal plane. All four ice-ocean models surveyed were subjected to forcing as specified by the AOMIP project. It should be noted that these four are only a small sample of models used by the high-latitude oceanographic community. There likely exist models that perform better (or worse) under the same surface forcing, and likewise these four models are known to perform better with a different choice of restoring of surface salinity [e.g., *Gerdes et al.*, 2003; *Drange et al.*, 2005], surface forcing, and model domain (e.g., extended to the global domain or to the tropical Atlantic). While the focus is on model intercomparison, observed data are used to gauge model success. The primary objective is to analyze the space and time variability of simulated upper-ocean temperature, salinity, and density at 200 or 234 m, which are used as a proxy for winter mixed layer properties, and to identify time periods when the upper-ocean waters were the densest. Such periods are likely to coincide with periods of deep convection in the Greenland Sea.

[22] The temperature, salinity, and density fields were investigated with respect to their mutual dependence regionally and their time evolution. The mutual correlations between salinity, temperature, and density fluctuations depict in principle the intrinsic properties of the water masses and their circulation. Time evolution at 75°N, particularly the evolution of Atlantic Water characteristics, exposes deficiencies of the experimental setups. One source of deficiency identified is the large role of advection in salt and heat balance along the track of Atlantic Water. Advection-associated changes can originate both from outside and inside the Nordic Seas to control the evolution of water masses together with the local thermohaline forcing. *Hátún et al.* [2005] show that the salinity of the Atlantic inflow to the Nordic Seas is controlled by the strength of the subpolar gyre, which by contracting and expanding controls the mixture of Atlantic Water entering through the Faroe Current. *Kauker et al.* [2005] show that temperature and salinity anomalies generated at 50°N, in contrast to barotropic fluctuations originating there, can easily be transported into the Nordic Seas. However, they also find that anomalies generated locally in the Nordic Seas can be of the same order as anomalies propagating within the North Atlantic Current. *Blindheim et al.* [2000] show that lateral mixing with Arctic waters is particularly active in the Norwegian Sea where the extension of the East Iceland Current brings very fresh waters. Model results point to a conclusion that the T-S evolution in the interior of the Greenland-Iceland-Norwegian Seas depends on the boundary conditions at the Nordic Sills, as evidenced by the success of the UW and GSFC models for Atlantic Water temperature evolution. However, salinity evolution remains problematic in all four models, even in the UW and GSFC models, which receive their boundary information from a much larger domain (see Table 1). The location of the southern boundary south of the Nordic Sills and including most of the subpolar gyre into the model domain, as in the AWI and the UL models, is not adequate to prevent a drift. The apparent requirement for boundary information (for both hydrography and momentum fluxes) from the main North Atlantic Ocean is based on the importance of meridional overturning changes in the high latitude (north of 45°N) salt balance [*Häkkinen*, 2002]. It is also evident that further improvement to Nordic Seas simulation can be provided by higher resolution in order to capture the detailed topographically controlled circulation patterns (as evidenced by the AWI and UW models).

[23] These comparisons show that modeling the Nordic Seas-Arctic system must undergo significant improvements in order to simulate the system's evolution realistically. Based on a short, 50-year record of observations, we can establish intrinsic relationships of the water masses, although we have no information about how the system behaves on a much longer-term basis, over hundreds to thousands of years. One property in question is the salinity-dominated maximum density of the upper ocean in the central Greenland Sea, which was successfully simulated by two of the models, although one of them switches from a salinity-dominated regime to a temperature-dominated regime. In the two other models the density maximum was determined by the coldest temperature. These differences reflect interactions of locally and remotely forced thermohaline effects on water masses which are strongly steered by topography. Increasing model resolution will likely help to account for strong topographic control on circulation. This should also improve simulations of high-latitude stratification where advection of heat and salt is an important part of local heat and salt balance. Research is also needed in the area of surface fluxes, since at present the matching of model setup and forcing data sets from observations is a matter of either gamble or tuning, while surface restoring involves damping feedbacks. One probable way out of this dilemma may be introduction of flux correction (see *Köberle and Gerdes* [2007] for a discussion). It is also apparent that the Nordic Seas are not insulated from main North Atlantic influences, which suggests the need to expand beyond regional Nordic Seas–Arctic models.